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TECHNICAL REPORT
QMRD-5

QUALITATIVE PHOTOELASTIC GELATIN STRESS ANALYSIS
OF THE
EFFECTIVENESS OF VARIOUS GROUND ANCHORING DEVICES

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OCTOBER 1955

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Quartermaster Research & Development Center, U S Army
Natick, Massachusetts

MECHANICAL ENGINEERING DIVISION
PIONEERING RESEARCH DIVISION

Technical Report
QM RD - 5

A QUALITATIVE PHOTOELASTIC GELATIN STRESS ANALYSIS OF THE
EFFECTIVENESS OF VARIOUS GROUND ANCHORING DEVICES

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Project References:

7-99-01-001

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October 1955

Foreword

Many of the large tents employed by the Army are completely dependent upon satisfactory anchorage to the ground. The wide variety of soil types encountered in the field by our soldiers, coupled with the fact that new and larger tents are being utilized, has greatly increased the need for improved anchoring devices.

As long as portable shelters are the responsibility of the Quartermaster Corps, the study of tent pins and ground anchors will be an important phase of Quartermaster mechanical development work. Efforts in the past have admittedly given too little consideration to the soil-mechanics aspect of the problem. Emphasis has been on the design of the device rather than on its net effect on the soil stress pattern.

It is not intended that soil mechanics be given undue emphasis, but it is intended that this report will give at least a preliminary insight into the soil mechanics phase of the anchoring problem.

It is believed that this study will facilitate a more scientific approach to future tent pin and ground anchor design work.

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Contents

	<u>Page</u>
Abstract	iv
1. Introduction	1
2. Gelatin as a Photoelastic Material	1
3. Laboratory Apparatus and Technique	4
4. The Gelatin Mix	7
5. Ground Anchors and Stakes Tested	9
6. Discussion of Results	15
7. Acknowledgements	16
8. References	16
Distribution List	

Abstract

This study was made to demonstrate graphically the relative effectiveness of two basic types of ground anchoring systems. These systems use either: (1) the stake-type of anchor, which obtains much of its holding force from the friction existing between the surface of the stake and the soil; or (2) the plate-type of anchor, which derives most of its holding force from the weight and shear resistance of the "cone of earth" above the buried plate. Comparison of photoelastic data with actual field test data of ground anchoring systems is included to lend validity to this study.

A QUALITATIVE PHOTOELASTIC GELATIN STRESS ANALYSIS OF THE EFFECTIVENESS OF VARIOUS GROUND ANCHORING DEVICES

1. Introduction

Although the development of ground anchoring devices might seem to involve only the simplest of technical considerations, extensive field experience with numerous types of tie-down stakes and ground anchors reveals that the problem of anchoring is often given too little consideration. There are an increasing number of applications and uses for ground anchoring devices by the Armed Forces. Because of the nature of mobile warfare many items such as aircraft hangars, personnel and equipment shelters, and radar components must be secured to the earth with quickly installed anchoring devices. It is hoped that this preliminary study will provide graphic evidence of the advantage of plate-type ground anchors over the more familiar stake-type ground anchors. This paper shows that plate-type anchors located relatively deep in the soil, develop much more favorable stress patterns than conventional tent pins and therefore possess greater strength-weight ratios. This investigation is believed to be the first to demonstrate photoelastically (in gelatin) the simulated soil stress patterns generated by actual full-sized anchors and stakes.

The technique of employing gelatin in soil mechanics studies to simulate actual earth masses has been in use for approximately fifteen years. In order to insure that the results obtained with gelatin models are valid, the similarity of the model and the actual structure must be carefully considered. If the necessary conditions are met, previous studies show that the results obtained with the model have a high degree of validity.³

In essence, the stresses and strains in the model system must be accurately proportional to those in the actual system. This requires that both systems obey Hooke's Law at all times, that the geometric shapes be similar and that the applied forces be proportional. If these conditions are met, stress at any point in the gelatin model will be proportional to the stress at the corresponding point in the actual system. As will be shown later, the results obtained with gelatin models in the present study are in good agreement with actual field tests.^{11,12,13.}

2. Gelatin as a Photoelastic Material

In photoelastic stress analysis, polarized light is passed through a transparent medium. A medium suitable for stress analysis becomes doubly refracting when subjected to stress, so that a stress pattern of

interference lines becomes visible. Where the lines are closest together the stresses are greatest. The transparent material used in the present study was a standard commercial gelatin.* It is somewhat of a surprise to most people that gelatin, normally used as food, is also a valuable engineering material. One of the first photoelastic gelatin stress studies was accomplished by Knappen and Philippe,⁶ in 1936. They used gelatin models to simulate a foundation and lead shot to simulate an embankment. These authors stated that gelatin was the only material known that would give satisfactory results in a study of this kind.

Extensive use has been made of gelatin in analyses of earth-dam structures and embankments.⁹ The extreme stress-optical sensitivity of gelatin, which is 200 to 1,000 times that of other photoelastic materials, enables models to be constructed in which the weight of the model itself is sufficient to give visible stress patterns. This is an important factor when, for example, the effect of the self weight of beams is being studied. No attempt will be made to present the complete theory of photoelastic stress analysis. A complete and effective treatment of the theory has been given by Frocht,⁴ Hetenyi,⁵ and Timoshenko.¹⁰

In 1940, Farquharson and Hennes³ utilized the gelatin technique in studying shear stress distribution patterns for the approach tunnel of the Lake Washington pontoon bridge near Seattle. Their account of this work contains considerable technical data helpful in making practical use of gelatin in soil mechanics research.

Cuykendall¹ of Cornell University has made an experimental determination of foundation stresses of gravity dams using the photoelastic-gelatin technique. He was also one of the first to realize the importance of gelatin in stress analysis. The main interest in his work was the effect of slope of a dam on the toe stresses.

At the 1948 Rotterdam Conference on Soil Mechanics and Foundation Engineering, Philippe and Mellinger⁸ presented the results of their studies of stresses in wall structures and earth embankments. They concluded that gelatin has a greater useable optical sensitivity than any other known material. Whereas glass, lucite, or celluloid must generally be strained nearly to the breaking point to obtain satisfactory stress patterns, gelatin gives good patterns long before the elastic limit is reached. Proportionality of stresses in model and actual structure is thus more readily maintained.

* Swift and Company's "Atlas"

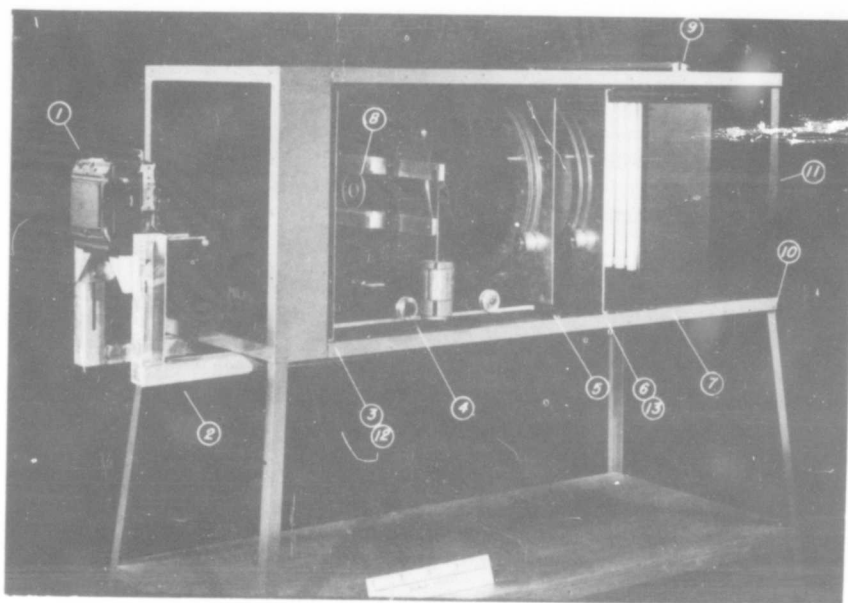


Figure 1 Diffusion-type Polariscope, 16" diameter

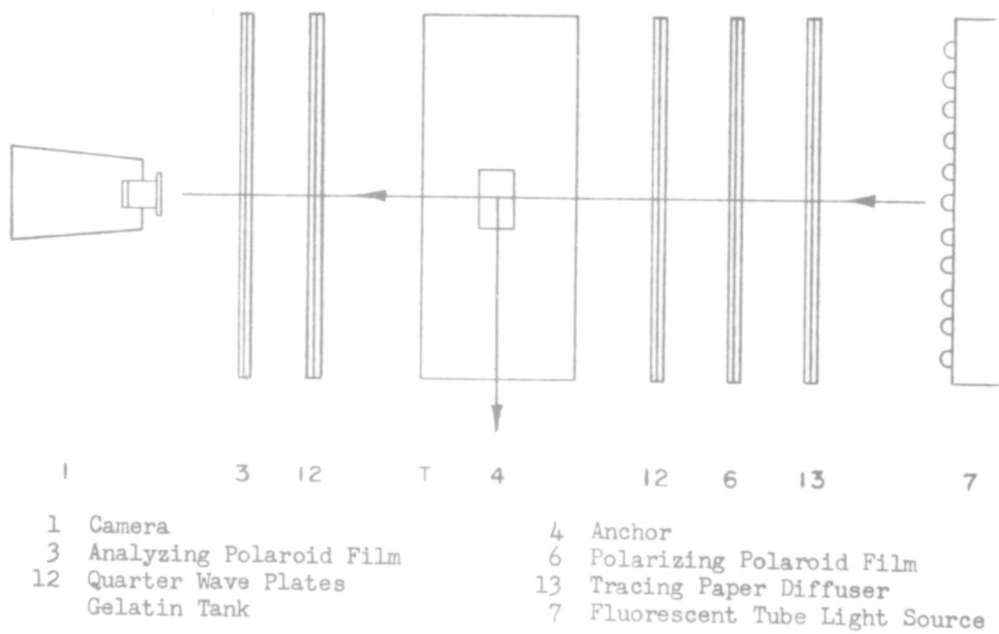


Figure 2 Schematic diagram, diffusion-type Polariscope

3. Laboratory Apparatus and Technique

The apparatus used in the present experiments is shown in Figs. 1 and 3. The arrangement of the basic components is shown schematically in Fig. 2. The basic components are indicated on Figs. 1 and 2 by the same reference numbers

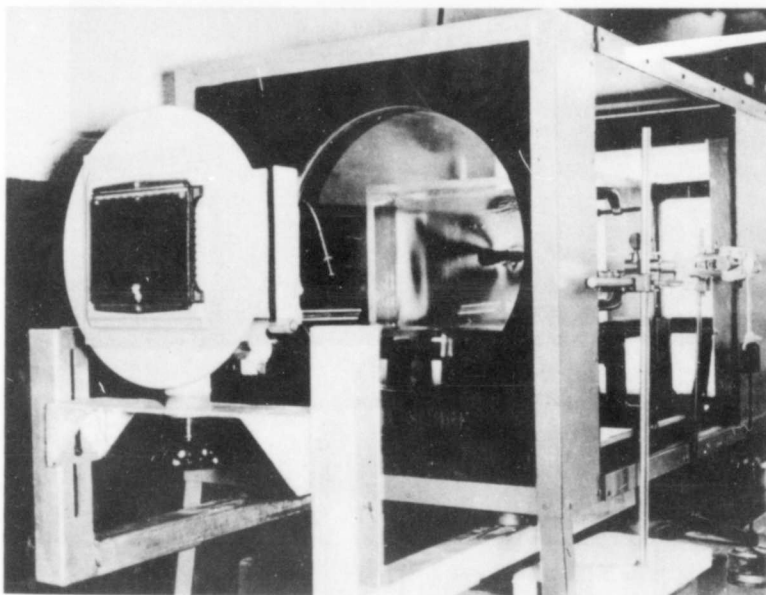


Figure 3:
Polariscope

The polariscope consists of a homemade 16-inch diameter field, diffusion-type optical bench similar to those used by Durelli² and by Leven.⁷ The polarizer (6), analyzer (3) and quarter wave plates (5 and 12) are constructed of polaroid sheets,* each sandwiched between two plates of 1/8-inch thick Plexiglas plastic. The Plexiglas plates protect the fragile polaroid sheets and form a rigid assembly that can be handled conveniently. Each of these sandwiched films is in turn bolted to a circular aluminum frame and mounted in the polariscope on three guide wheels as shown in Fig. 1, so that it can be rotated freely when desired.

The diffusion plate (13) was a sheet of ordinary tracing paper sandwiched between two sheets of 1/8-inch Plexiglas. This diffuser was entirely satisfactory and is less expensive and more durable than the ground glass ordinarily used.

*Polaroid Corp., Cambridge, Mass.

The light source for the polariscope consisted of twelve 15-watt fluorescent light tubes mounted in a steel framework (7). A sheet of aluminum is located immediately behind the fluorescent tubes to serve as a reflecting surface. The lighting unit is unique in that it is a plug-in type unit that enables the entire assembly to be removed from the polariscope in less than 5 seconds. This special feature facilitates quick and convenient change-over from white to semi-monochromatic green light and vice versa. In the present study, only white light was used. This is satisfactory for a qualitative analysis, such as this. In quantitative work monochromatic, circularly polarized light would be preferable.

The diffusion-type polariscope that was used is admittedly less accurate than those employing lens systems; however, the cost of the lens system required to give a 16-inch diameter field would be prohibitive. The large 16-inch field permits full-scale study of many items that would have to be greatly reduced in size to conform to the 3-inch diameter field often used with lens systems.

Two different gelatin tanks were used at various stages of the research. The first tank was fabricated from Plexiglas plastic plates 1/4-inch thick, which were held together with brass machine screws and cemented with acetone. The outside dimensions of the tank are approximately 7 inches deep, 18 inches wide, and 16 inches high. The second tank, of 1/2 inch thick plexiglass plate, was 10 inches deep, 16 inches wide, and 12 inches high. It employed tongue-and-groove joints cemented with plexi-glue and proved more satisfactory and less inclined to leak. In most of the previous work in which gelatin has been employed, the gelatin has seldom been more than 4 inches thick and has sometimes been only 1 inch thick. The size of the tank in this study was determined not only by the size of the anchoring devices tested, but also by the anticipated size of their stress patterns.

The inside of the plastic tank which contained the gelatin was coated with mineral oil or vaseline to reduce friction and gelatin surface strain.

The general manner in which the various anchoring devices were arranged in the gelatin tank is shown in Fig. 4. The specimens were suspended in the liquid gelatin by temporary rigging until the gelatin hardened. The 50° angle of pull used in most of the experiments was adopted on the recommendation of the Tentage Branch, Quartermaster Research and Development Center.

All photographs used in this report were taken with white light. A Burke and James camera of the type generally used in metallurgical work was used. The lens was a Wollensak-Raptar 16 mm. and the plate size was 4 x 5 inches. The distance from the camera lens to the gelatin tank was approximately 25 inches.

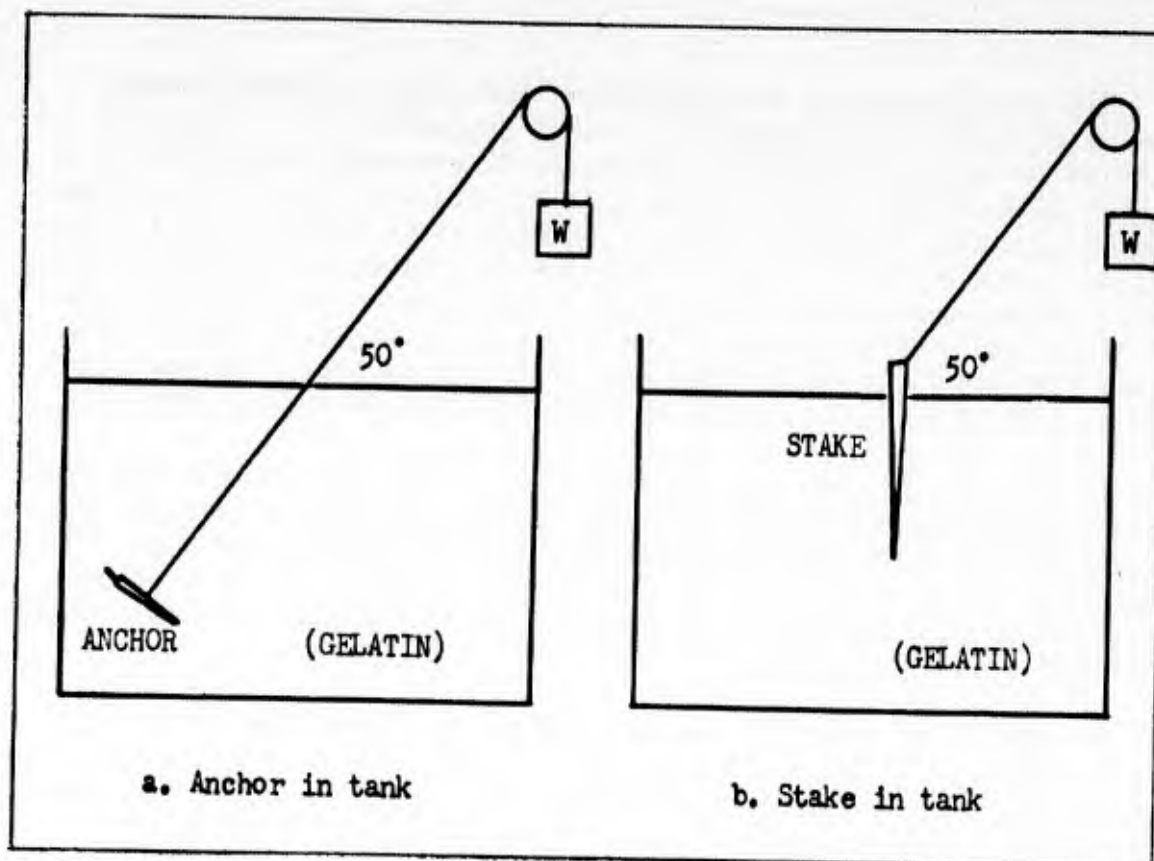


Fig. 4 General Arrangement of Anchor and Stake in Gelatin Tank.

The first photographs were made using panchromatic* No. 428 film with an f5.6 shutter opening. Later in the work, Isopan** film was used. Exposures of 1/2 a second were found to be satisfactory for the top views and 1 second for the normal or side views. Longer exposures were necessary for side views because the light had to travel through two layers of 1/2 inch Plexiglas in that view, as compared with only one layer in the top view.

A two-view technique was employed in most of the analyses. The gelatin tank, rather than the camera, was moved to achieve this. Fig. 3 shows the gelatin tank on its side in the polariscope, with the top of the tank toward the camera. This position gives a top or plan view. For side views the gelatin tank was rotated 90°, so that the side of the tank was toward the camera. By using this two-view technique, regions of critical

* DuPont No. 428

**Ansco Isopan

stress were more accurately located within the gelatin mass. Some of each type appear in this report.

4. The Gelatin Mix

After a study of gelatin mixes previously used for soil stress problems, the following composition was selected:

	<u>Weight (%)</u>	<u>Volume (%)</u>
Gelatin	13	20
Water	52	52
Glycerin	34	27
Phenol	1	1

The yield is about 80 percent of the volume of the unmixed constituents. Much conflicting information on the best methods of mixing the constituents and the most satisfactory procedure for melting the gelatin is to be found in previous reports. The technique used here was developed by trial and includes a few innovations.

The mixing was performed as follows: Tap water and glycerin were thoroughly mixed at room temperature and phenol added. Approximately 1/10 of the liquid was placed in a container and 1/10 of the dry gelatin sprinkled into it. More liquid and more gelatin powder were then added in successive layers until all had been added. The advantage of this procedure is that it eliminates the need for stirring and keeps the formation of large bubbles to a minimum. The mixture was permitted to stand overnight so that the water and glycerin would all be absorbed into the gelatin before the mixture was heated. The slight formation of foam which gathered at the surface of the melting gelatin was removed by skimming a straight edge over the surface. The gelatin thus mixed had a faint amber color and was highly satisfactory from the standpoint of transparency. It was sensitive enough to give good patterns under load and yet tough enough to withstand reasonably heavy loading. It was not found necessary to resort to filtering or to clarifying with egg whites as is sometimes done.

The technique developed for melting and cooling the gelatin will be described in detail because it was found that this was one of the most crucial steps in obtaining a stress-free mass. Best results were obtained by immersing the gelatin in a large water bath at a temperature of about 140°F. The melting normally required about 4 hours, after which the gelatin was allowed to cool gradually. The water bath was maintained at proper temperature by manual control of an electric hot plate located under the water bath. When the water bath was left in

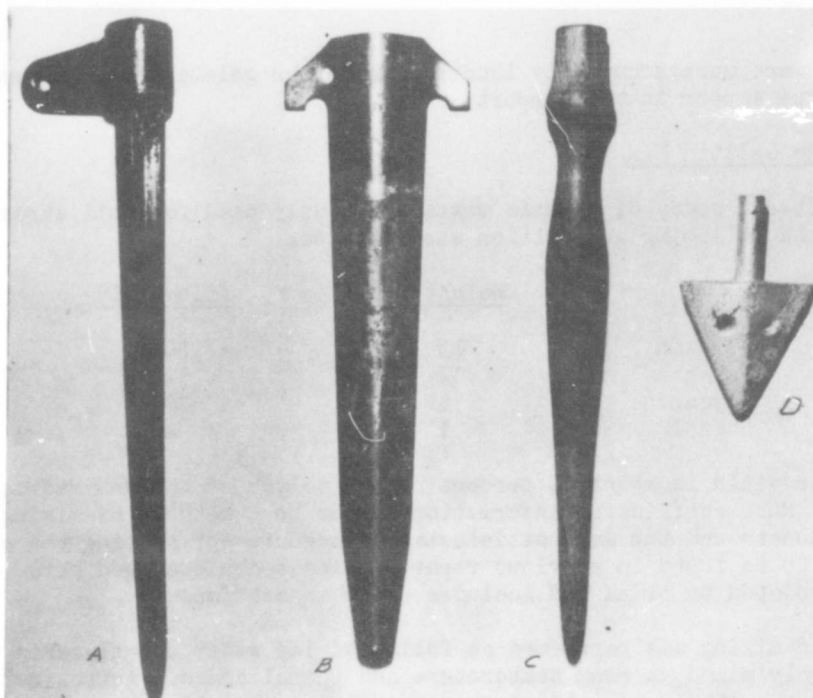


Fig. 5 Various Tent Anchoring Devices

- A. East German 9-inch Magnesium Bayonet-Type Tent Pin.
- B. Standard U.S. Army 9-inch Aluminum Tent Pin.
- C. Standard U.S. Army 9-inch Wooden Tent Pin.
- D. Experimental U.S. Army 2-inch Aluminum Ground Anchor.

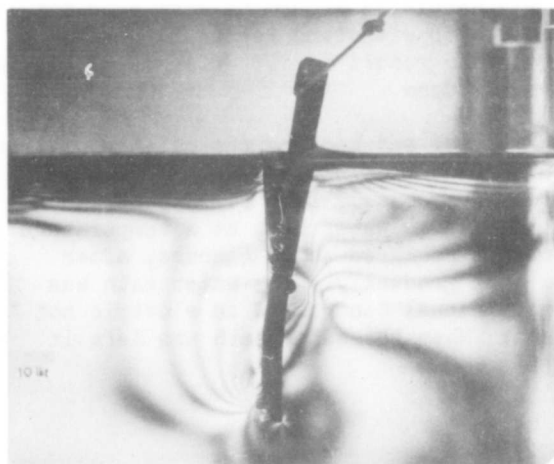


Fig. 6 Side View of Stress Pattern of 9-inch Aluminum Tent Pin Under a 10-Pound Pull.

place and the cooling allowed to take place overnight, residual strain in the gelatin was practically eliminated.

The use of 1 percent of phenol in the gelatin mixture completely prevented the growth of visible mold; this was highly gratifying. Early experiments in which phenol was not used had to be discontinued because of rapid mold growth in the gelatin. One large gelatin specimen which contained 1 percent phenol was used for two months in a room held at a temperature of about 75°F. without noticeable formation of mold. This specimen was melted and reused 6 times and gave consistently good stress patterns.

A few precautions to be taken when working with gelatin will be mentioned. The mixture sometimes contains lumps that must be removed by straining. Copper or brass screen should not be used for this purpose because they produce a bad discoloration. Evaporation of water from a gelatin mix can become troublesome. The resultant shrinkage introduces undesirable strains into the gelatin, especially at the exposed surfaces. In these experiments evaporation was controlled by keeping the gelatin tank covered when not in use. On a few occasions, a moist sponge was placed inside the tank but not in actual contact with the gelatin mix.

5. Ground Anchors and Stakes Tested

There have been hundreds of different types and sizes of anchoring devices developed. However, only a few of these have been adopted by the Army. For purposes of this study actual full-sized anchors and stakes were used. This had two advantages. It eliminated the expense of preparing small-scale models and it gave large stress patterns that could be readily photographed and interpreted.

Three pins (stake-type) and one drive-type ground anchor were used. Even with the large polariscope and gelatin tanks, use was still limited to the smaller sized anchoring devices, but it is thought that the results will generally be valid for the larger sizes as well.

The first tent pin investigated was the standard Quartermaster 9-inch aluminum pin now used with the majority of small army tents. It is shown in Fig. 5B. It has an angle cross-section and weighs about 3 ounces. After extensive field tests, this pin was accepted by the Army to replace the more bulky wooden pin previously used. The 9-inch aluminum pin will hold several hundred pounds in frozen muskeg, from 50 to 200 pounds in hard unfrozen soil, and up to 25 pounds in sand. Fig. 6 is a side view photograph of the 9-inch aluminum pin immediately prior to pulling out of the gelatin, at a maximum load of 10 pounds. Efforts to exceed the 10-pound load with this pin failed. The high degree of

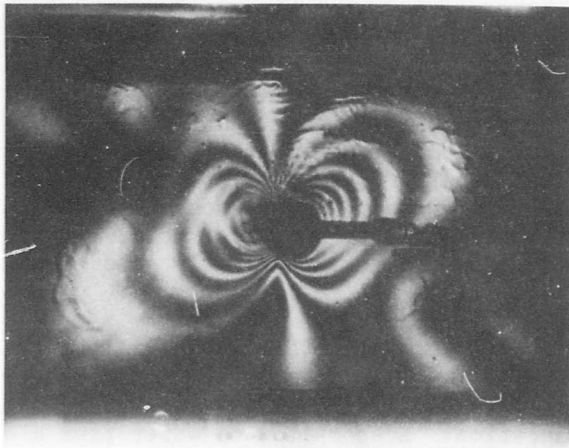


Fig. 7 Top View of Stress Pattern of Bayonet-Type Tent Pin Under an 8-Pound Pull.

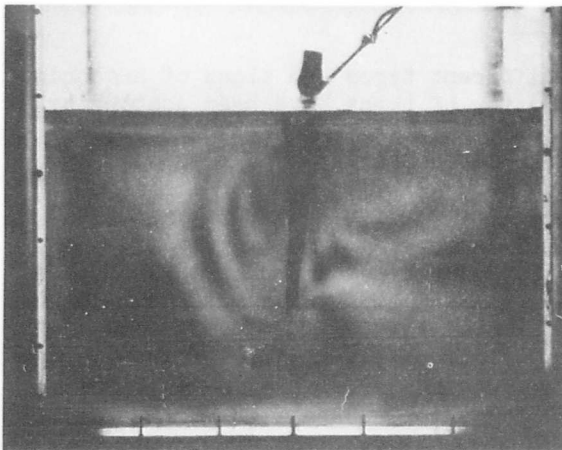
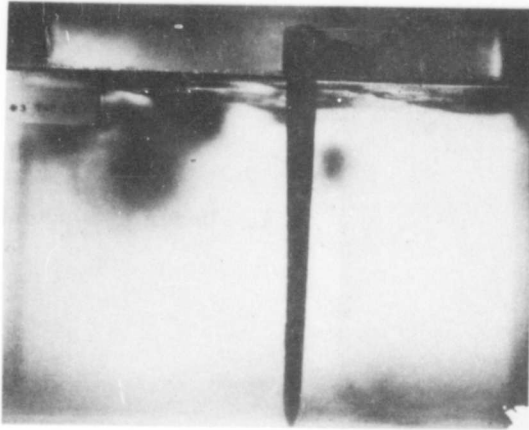


Fig. 8 Side View of Stress Pattern of Wood Tent Pin Under a 7-Pound Pull.

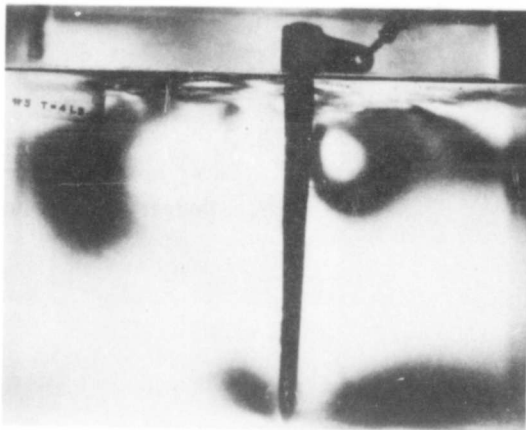
stress concentration visible at the surface of the gelatin is significant. The stress lines are so close together at the surface that they appear to merge into a single black band. Fig. 7 shows a top view of a similar pin. The stress pattern is typical of all the pins studied.

The next pin utilized was the standard Army 9-inch wooden "pup tent" stake, shown in Fig. 5C. It is circular in cross-section and weighs from 1 to 3 ounces, depending on the type of wood. This pin is capable of holding loads up to approximately 150 pounds, if soil conditions are favorable. In sandy or frozen soil, it is a poor ground anchoring device. Fig. 8 shows the 9-inch wooden pin being pulled out of the gelatin at a load of only 7 pounds. It was this photograph that first prompted adoption of the two-view technique. The region of maximum stress is very near the surface and is much more readily observable in a top view, as shown in Fig. 7, rather than in a side view as shown in Fig. 8.

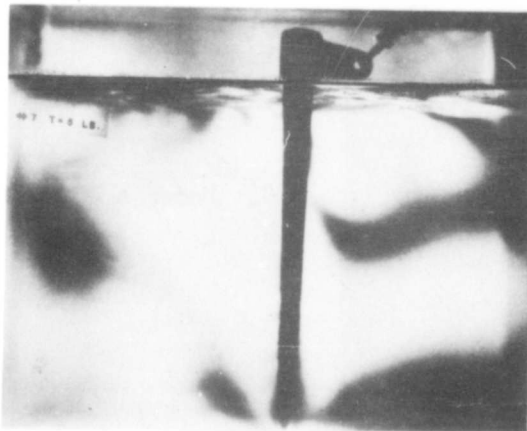
The third item studied was a cast magnesium bayonet-type stake obtained in East Germany. It is shown in Fig. 5A. This pin weighs about 2 ounces and is nearly 10 inches long. Field tests showed that this pin was suitable for hard clay and would hold up to 400 pounds where the



A. Under a 2-pound pull

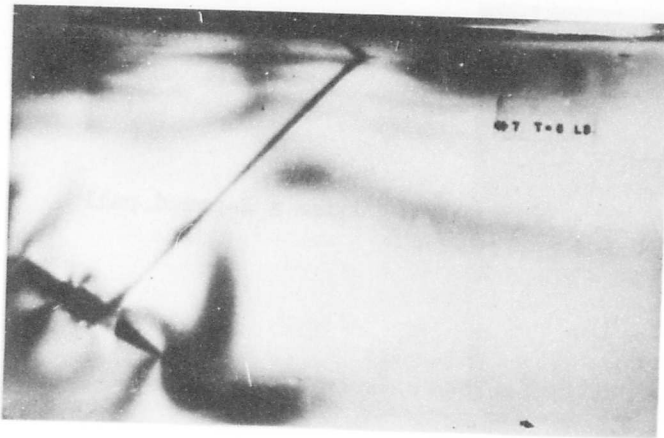


B. Under a 4-pound pull



C. Under a 6-pound pull

Figure 9 Side view of stress patterns of bayonet-type tent pin



A. Under a 6-pound pull



B. Under a 19-pound pull



C. Under a 28-pound pull

Figure 10 Side view of stress pattern of ground anchor under various pulls

ground was frozen or very compact. Like other tent pins, this item provides very little holding force in sandy soil. Figs. 9A, 9B, and 9C are side views of this stake at loads of 2, 4, and 6 pounds, respectively. The maximum load for this stake was 8 pounds. Fig. 7 shows a top view of the same stake. Other types of tent pins produced essentially the same characteristic stress patterns as those shown, with the greatest stress located near the gelatin surface.

The fourth and last item studied was the new* arrow-shaped ground anchor shown in Fig. 5D. It weighs less than 1 ounce and is a little more than 2 inches long. This ground anchor is driven to a depth of from two to three feet into the ground by using a sledge hammer and a piece of pipe. The pipe (driving tool) is placed over the spindle portion of the anchor before driving and removed from the ground after the anchor has been driven to the desired depth with the hammer. The guy wire or cable is attached to the anchor plate before it is driven into the ground. This new anchor is self-orienting in the ground so it is not necessary to drive it in at any specific angle. In frozen soil, it has held 4,200 pounds when driven to a depth of only 9 inches, and in hardpan (unfrozen) it has held in excess of 2,000 pounds at a depth of 26 inches. Unlike the tent pins, it will also give a reasonable holding force (300 lb.) in sandy and gravelly soils, when driven to a depth of from two to three feet. Figs. 10A, 10B and 10C are a series of side views of the stress patterns of this anchor in gelatin, at loads of 6, 19, and 28 pounds, respectively. Fig. 11 is a top view of the same anchor at a load of 20 pounds. The maximum pull withstood by this anchor in gelatin was 65 pounds.

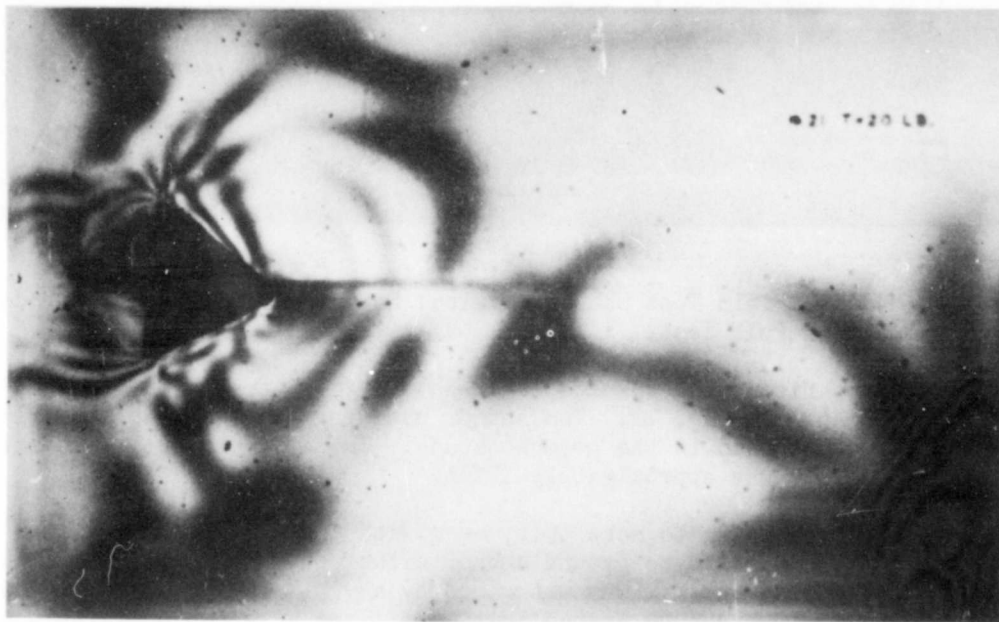


Fig. 11 Top View of Stress Pattern of Ground Anchor Under a 20-Pound Pull.

*U.S.P. No. 2,712,864, July 1955.

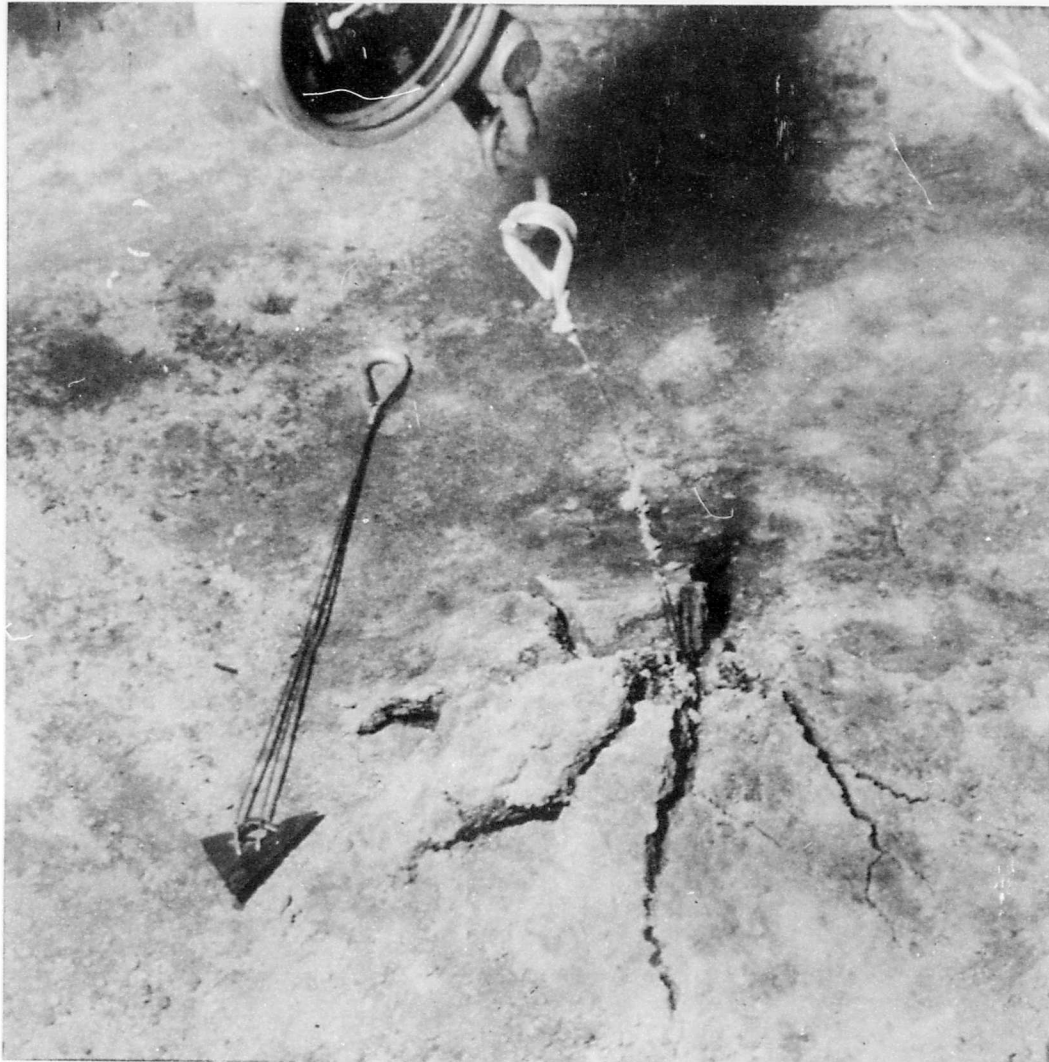


Fig. 12 Actual Field Test Showing Typical Soil Failure Caused By Ground Anchor Ultimate Pull Test.

For comparison, the results of an actual field test¹² of a ground anchor are shown in Fig. 12. The anchor used in this test was an early model of the one used in the present study. The ultimate pull when soil rupture occurred was approximately 1 ton.

It is interesting to note that, even with the relatively shallow gelatin tank, the new type ground anchor withstood a pull more than six times greater than the maximum withstood by any pin (65 lb. as compared with 10 lb.). It might be argued that conditions were not comparable and that the pins should have been buried to the same average depth as the anchor. However, in actual use the pins are not normally buried, whereas the anchor is. Therefore, test conditions used are in accord with actual

practice. In fact, it is possible in actual use to bury the ground anchor more deeply than it would be buried in the gelatin tank, so that in practice the anchor might well hold more than six times as much as a comparable tent pin.

6. Discussion of Results

As indicated in the title of the paper, this is a qualitative rather than a quantitative study. However, some significant conclusions can readily be drawn simply by inspecting the stress patterns. For the tent pins there are two regions of stress concentration. One is somewhat below the surface of the gelatin, on the side where compression is produced by the pull of the load. The other is near the tip of the pin and on the opposite side. Figures 9A, 9B and 9C show rather well the increase of stress in these regions as the pull on the stake is increased. At 2 pounds (Fig. 9A), the upper region at the right of the stake is visible as a black spot, while the lower region is not yet visible. At 4 pounds (Fig. 9B), the region at the lower left of the stake is visible as a black spot.

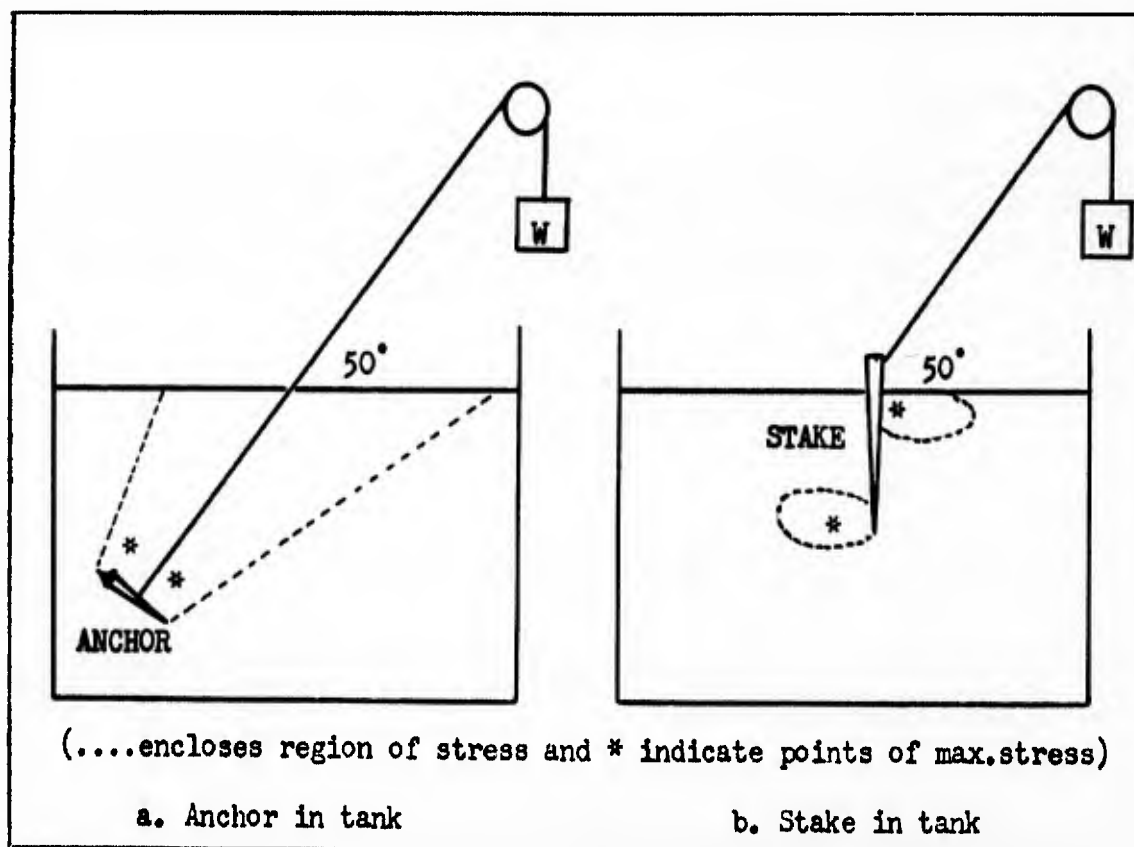


Fig. 13 Schematic Diagram Showing Regions of Stress (enclosed by dotted lines) and Points of Maximum Stress (indicated by crosses).

The stress in the upper region has increased until the center is again white, surrounded by a black ring. Fig. 9C shows a still more advanced stage at a load of 6 pounds. There are other regions of stress concentration visible in the photographs. To some extent these are associated with residual stresses and were evident before the application of load. It is believed, however, that the stresses at the upper right and lower left of the stake are the important ones to be considered as failure begins. These regions are indicated schematically in Fig. 13. Tent-pin stress patterns normally show a region of stress concentration near the surface of the gelatin extending all the way to the edges of the tank. However, we do not believe that the stresses in this layer are as important in predicting failure as those indicated in Fig. 13.

The stress pattern of the ground anchor (Figs. 10A, 10B, 10C, 11) is quite different from those of the stakes. Instead of two small critical regions of stress concentration, there is one large region. This region is essentially a truncated cone beginning at the anchor and extending to the surface of the gelatin, as indicated schematically in Fig. 13. It is obviously desirable to have one large region of moderate stress concentration rather than two small regions of high stress concentration. This is the basic reason for the superiority of the ground anchor over the tent stake, as regards holding power.

7. Acknowledgements

Acknowledgement is made to Dr. W. M. Murray, of the Massachusetts Institute of Technology and Dr. Harold J. Hoge and Mr. C. H. Philleo of the Quartermaster Research and Development Center for helpful suggestions and guidance. Thanks are also due to Mr. W. Caskie and his staff for the fabrication of the special apparatus employed.

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